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FLOW STRESS OF V, Mo, Ta, AND W ON NANOSECOND TIME SCALES

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Abstract. The mechanisms and kinetics of plastic flow in body-centered cubic materials are of current interest in the development of fundamental theories of dynamic strength, applicable at high strain rates such as are found in high explosive and laser loading. We have performed dynamic loading experiments with the Janus and Trident lasers, using tailored pulse shapes to induce shock or ramp loading. The response of the sample was investigated through the surface velocity history, and in some cases with in-situ x-ray diffraction. The velocity histories exhibited clear elastic waves, from which the flow stress was deduced and compared with the elastic strain as determined by diffraction. We compare the deduced flow stress with models calibrated to samples millimeters thick, and to theoretical studies.

Keywords: shock, plasticity, solid-solid transition
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INTRODUCTION

Constitutive models to describe the behavior of materials under dynamic loading should be based on the underlying physics of the deformation processes in order to be predictive over a wide range of loading conditions. BCC metals are of particular interest because of the considerable number of engineering materials with this crystal structure (e.g. Fe) and also the large number of metals which melt out of the BCC structure (e.g. Be) and whose strength under extreme conditions of dynamic loading is of technological interest (e.g. for inertial confinement fusion energy). Interesting aspects of dynamical behavior include the competition between slip and twinning, brittleness, the interplay between plasticity and phase transitions, and variations in elastic and plastic anisotropy.

We have investigated the response of several BCC metals to dynamic loading with relatively high strain rates, $\sim 10^7 - 10^9$/s, with loads induced by laser ablation. One attraction of laser loading is the ability to alter pressure and strain rate relatively easily through changes in the irradiance history. Kilojoule-class lasers also make it feasible to perform x-ray diffraction *in-situ* of the transiently-compressed state. Here we present a digest of results from several series of experiments performed over the past few years at LANL and LLNL.

EXPERIMENTAL METHOD

Dynamic loading was induced in samples by direct ablation of one surface of the sample by laser irradiation. Laser pulses of 2.5-10 ns duration were used, and irradiances of a few to a few tens PW/m^2. Controlling the power history of the laser, ablation in this regime has been demonstrated previously to induce predictable shocks and ramp compression in metallic elements and alloys, without deleterious effects from x-ray preheat or thermal conduction [1, 2, 3]. The response of the sample was determined primarily through the surface velocity history at the opposite side of the sample, measured using laser Doppler velocimetry of the line-imaging VISAR type [4, 5]. The elastic-plastic and tensile failure of the sample are manifested as features in the velocity history in a similar manner to impact experiments. The main differences are that the pressure in the sample is sustained directly by surface ablation for the duration of the laser pulse rather than by the shock and release transit time through the impactor, and a small proportion of the sample thickness is removed by ablation.

In each experiment, the sample was clamped by the edges in an evacuated target chamber, and a diffractive optical element was used to give a spatially uniform laser irradiance. In some cases, samples of different thickness were mounted side-by-side, allowing the compression and release waves to be observed after propagating different distances. For the thinner samples of V, a second laser beam was brought to a tight focus on a nearby foil of Ti, producing a pulse of x-rays of 4.7 kV which were collimated into a narrow beam and used to observe the perturbation of diffraction lines, and thus crystal lattice spacings, in the sample. Diffraction from shocked, polycrystalline samples was demonstrated previously in Be with recording on time-resolving x-ray streak cameras and time-integrating film [6]. For the V samples, the diffraction patterns were recorded using time-integrating image plates, bent into a cylinder coaxial with the incident x-ray beam [7]. This cylindrical geometry is geometrically elegant in that diffraction cones appear nominally as straight lines when the image plate is unrolled. Slight distortions occur, because of the seam along the cylinder and the presence of holes for the drive beam and surface velocimetry. (Fig. 1.)

Some of the samples were clamped against a transparent LiF window through which the surface velocity was measured. These samples were almost always recovered intact and with little two-dimensional deformation evident, even at high drive pressures. Some of the other samples were also recovered, particularly the thicker V samples, with varying degrees of bowing. Metallography was performed on some of the recovered samples.

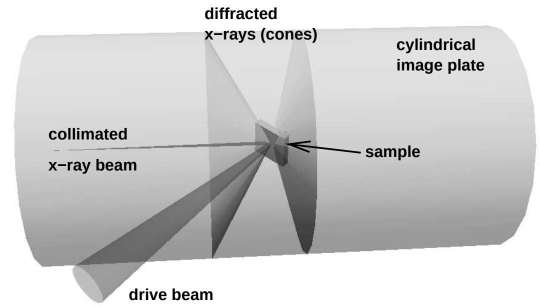

FIGURE 1. Experimental schematic.

RESULTS

Experiments were performed on rolled foils of V, Mo, Ta, and W, a few tens of micrometers thick, and on V samples several hundred micrometers thick which were cut from a polycrystalline plate (Table 1). For the foils, laser pulses of less than 10 ns were sufficient to induce shocks that will traverse the whole sample without being caught and eroded by the release as the ablation pressure fell [8]. However, the thicker V samples required the driving pressure to be sustained for over 10 ns, which was possible – with some difficulty in controlling the pulse shape – at the Janus laser.

The Ta and V foils were loaded with both shocks and ramps. The Ta experiments were performed at the Trident laser, with a maximum pulse length of 2.5 ns. The ramp occupied almost the whole of the pulse, with no time left to sustain the peak pressure, so the peak pressure decayed as the ramp propagated through the sample. In contrast, the V experiments at the Janus laser used a pulse in which the peak pressure was held for ~ 2 ns, and it did not decay as it propagated through the sample.

In a typical experiment, an elastic wave was visible, followed by a plastic wave to the maximum surface velocity, then deceleration limited by tensile failure. The surface acceleration, reflecting the strain rate, was significantly lower with ramp loading. (Figs 2 and 3.)

Where possible, the flow stress Y was estimated from the amplitude of the elastic wave in the velocity

TABLE 1. Summary of experiments

		thickness (μm)	**pressure** (GPa)	**drive**
V	plate	300-400	15-30	8-12 ns shock
V	foil, 99.8%	25-40	5-70	4 ns shock; 3+2 ns ramp
Mo	foil, 99.9%	15	50-60	2 ns shock
Ta	foil, 99.9%	25-75	5-30	2.5 ns shock & ramp
W	foil, 99.95%	25-50	5-100	2.5 ns shock

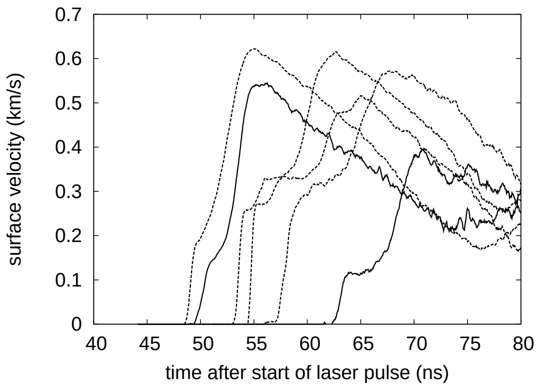

FIGURE 2. Surface velocity histories from V cut from plate, shock-loaded, showing variation in precursor amplitude and shape. Solid lines are from samples of different thickness mounted side-by-side.

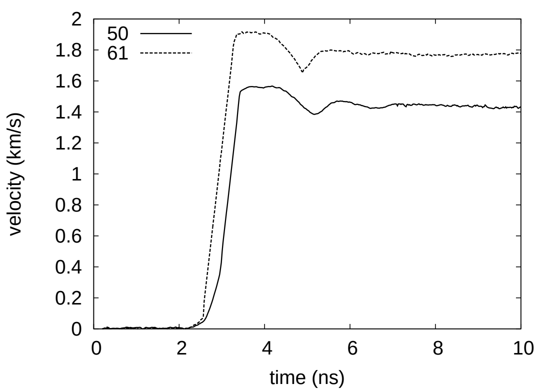

FIGURE 3. Surface velocity histories from shock-loaded Mo foils, 15 μm thick, as a function of drive pressure (GPa).

history, using the relations

$$Y = \frac{3}{2}\sigma_n\left[1-(c_b/c_l)^2\right] \quad : \quad \sigma_n = \frac{1}{2}\rho_0 u_p c_l.$$

Strain rates were estimated from the acceleration in the elastic wave. (Table 2.)

A particularly wide variation in flow stress was observed in V, correlated with the strain rate applied to each sample. Shock-loaded samples 25 μm thick apparently exhibited elastic strain almost up to the full pressure applied, whereas ramp-loaded samples of the same thickness exhibited flow stresses similar to or lower than those inferred from shocks in samples millimeters thick, represented by the initial flow stress Y_0 and maximum work-hardened flow stress $Y_{\max}$ in the Steinberg-Guinan (S-G) model [9]. Shock-loaded samples over 300 μm thick exhibited flow stresses roughly double the magnitude. Metallographic analysis showed that samples giving different flow stresses did not differ significantly in microstructure. Fewer measurements were made on the other metals. Although the flow stresses were significantly greater than the S-G values, the difference was less pronounced than for V.

The x-ray source and diffraction geometry were most sensitive to motion of the V (110) line. Under shock and ramp loading, this line was observed to move in both the reflection and transmission regions of the azimuth, corresponding respectively to strains parallel and perpendicular to the loading direction. In the shock-loaded samples, little perpendicular deformation was observed in the first nanosecond after loading was applied, but increased rapidly after a further nanosecond. This response time was consistent with the apparent large elastic precursor amplitudes in 25 μm samples. The ramp-loaded samples showed both components of strain in all cases. (Fig. 4.)

For loading pressures above 60 GPa, additional lines appeared in the diffraction record from V. Interestingly, this pressure matches the onset of a rhombohedral distortion of the BCC structure observed in diamond anvil cell experiments [10] and electronic structure calculations [11], though our experiments probed higher temperatures and shorter time scales.

TABLE 2. Flow stress.

	S-G Y_0 (GPa)	S-G $Y_{\mathbf{max}}$ (GPa)	this work (GPa)	strain rate (1/s)
V, 25 μm	0.6	1.23	0.4-0.9	$1\times10^7 - 1\times10^8$
			3.6-14?	$1\times10^8 - 4\times10^8$
V, 350 μm	0.6	1.23	1.1-1.8	$1\times10^7 - 2\times10^8$
Mo, 15 μm	1.6	2.8	2-5	$2\times10^7 - 2\times10^8$
Ta, 70 μm	0.77	1.1	1.6 ± 0.3	$2\times10^7 - 1\times10^8$
W, 25 μm	2.2	4.0	8.6 ± 0.3	$\sim 1\times10^8$

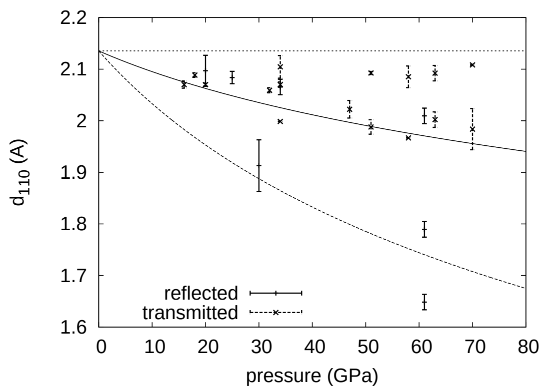

FIGURE 4. Motion of (110) diffraction line in V foils. Solid line is for hydrostatic deformation. Broken lines are for uniaxial deformation parallel and perpendicular to the loading direction (perpendicular showing no deformation), corresponding to ‘reflected’ and ‘transmitted’ points respectively.

CONCLUSIONS

Ablatively-induced shocks were driven through samples up to several hundred micrometers thick, using temporal shaping of the laser pulse to induce the desired loading history. Flow stresses in thin samples of all four BCC metals were higher than inferred in samples millimeters thick, and exhibited strong time-dependence. Diffraction data were collected from ramp-loaded samples of V, with the laser pulse designed to sustain the peak ramp pressure. The diffraction data showed effects of elastic strain at high pressure, apparently consistent with features in the surface velocity histories. New diffraction lines appeared above 60 GPa for shock and ramp loading. This threshold pressure is consistent with the observation of lines from the rhombohedral structure in quasistatic compression. On initial inspection, the new lines appear to be consistent with the rhombohedral structure, possibly with some elastic strain.

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